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On the manipulation of the magnetic forces for improving the contactless plucking in piezoelectric vibration energy harvesters

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Abstract. We propose a shielding technique for the magnetic field localization around permanent magnets (PMs) for sharpening the magnetic force-displacement curve in the frequency up-conversion (FuC) of piezoelectric vibration energy harvesters (PVEHs). We present a concept with theoretical formulation, computational analyses, and experimental validation that confirms the supposed principle. The numerical study on a PVEH shows that with the shielding, for varying actuation velocity, high values of peak power (50 mW – 150 mW) can be reached at low speeds (e.g. 0.5 m/s – 2.6 m/s). The unshielded device exhibits a good behavior for velocities over 3 m/s. This result makes the technique useful for the design of FuC mechanisms depending to its operating velocity.

Introduction

The manipulation of the magnetic field has been largely studied in the last decades because of immediate practical applications (e.g. electromagnetic induction heat treatments). The basic idea to manipulate the magnetic field is to exploit a magnetic flux concentrator (MFC) which is a piece of soft ferrous material with high magnetic permeability. As a consequence, the field lines are forced to follow a specific path in the surrounding space and they remain free to expand where there is not high permeability as shown in Fig. 1a.

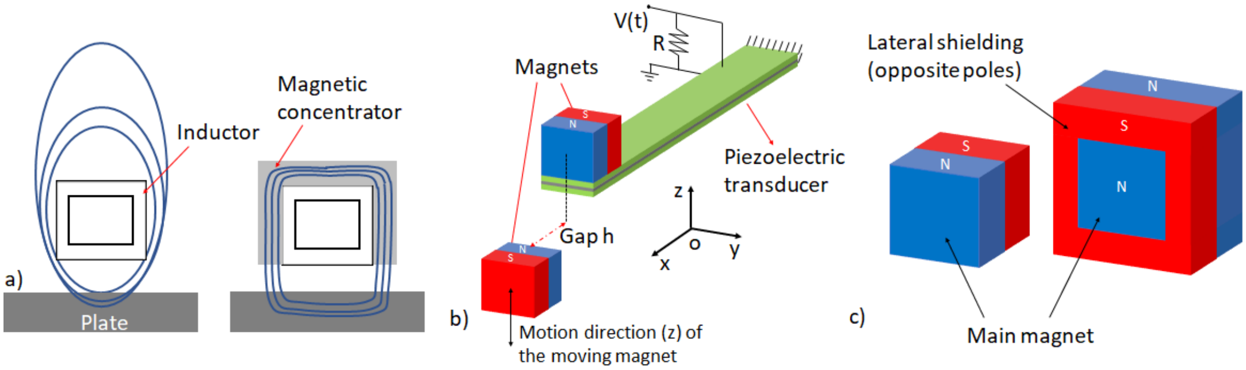

Figure 1. a) Illustration of the field lines path with and without the magnetic concentrator, b) proposed shielding layout of a PM with indication of the poles, c) PVEH with magnetic FuC

The approach can be used to control rapid temperature cycling (RTC) technologies as made by Mrozek et al [1], or to improve the gap-to-gap induction heating as proposed by Wen et al [2]. In the micro-electro-mechanical systems (MEMS) industry the MFCs are used to increase the sensitivity in Hall-effect based transducers [3]. The magnetic field can be also manipulated with high-rate triode sputtering of patterned thin films as made by Chigirinsky et al [4]. In this work we propose a technique of concentration with an innovative application on the contactless frequency up-conversion in PVEHs. The motivation is the fact that it is not always possible to have a real impulsive phenomenon [5] in plucking of transducers. To have an efficient mechanism also at a very low frequency or input velocities such in case of the human motion (e.g. 0.1-5 Hz), it is possible to tune the shape of the magnetic force by means of additional PMs.

Shielding technique

The magnetic plucking mechanism, as proposed in [6], is composed of a piezoelectric transducer equipped with a PM that magnetically interacts with another dynamical systems also equipped with a PM, Fig. 1b. In this framework the goal is the sharpening of the magnetic force with respect to the relative distance between them. The idea is to capture the field lines with additional PMs with an inverse poles orientation as indicated in Fig. 1c. The shielding material is put only on the sides of the central (main) magnet that contain both the poles (4 over 6 faces in a parallelepiped case). Both the main magnet and the material around it are made of Neodymium-Boron-Iron alloy (NdFeB). An important point is that the technique remains conceptually valid if either both or only one of the involved main magnets are shielded.

Mathematical modeling

In this section we present the modelling of the magnetostatics problem and the PVEH reduced order model.

Magnetostatics problem

In absence of electrical current, the first Maxwell's equation [7] in a domain Ω is:

$$\nabla \times \mathbf{H}=\mathbf{0} \qquad \text{in } \Omega \tag{1}$$

where $\mathbf{H}$ is the magnetic field density vector. The problem is conservative, and it is possible to define a scalar magnetic potential φ_M inside the domain:

$$\mathbf{H}=-\nabla \varphi_M \qquad \text{in } \Omega \tag{2}$$

Then we assume a linear constitutive law between the magnetic field $\mathbf{H}$ and the magnetic flux density $\mathbf{B}$ also by considering the magnetization vector $\mathbf{M}$ of the PM:

$$\mathbf{B} =\mu_0(\mathbf{H} + \mathbf{M}) \qquad \text{in } \Omega \tag{3}$$

where μ_0 is the permeability of the vacuum equal to $4\pi\text{e-}7$ N/A^2. It is then possible to write an equation of magnetic flux conservation by means of the Gauss' Law:

$$\nabla \cdot \mathbf{B} = \mathbf{0} \qquad \text{in } \Omega \tag{4}$$

Eqs. (1)-(4) must be considered together with the boundary conditions (BCs). A Neumann BC, also called insulation equation, can be put on symmetry planes where the magnetic field is tangential to the plane:

$$\mathbf{n} \cdot \mathbf{B} =0 \qquad \text{on} \qquad \partial\Omega_{\text{ins}} \tag{5}$$

where $\mathbf{n}$ is the normal outward unit vector and $\partial\Omega_{\text{ins}}$ is the insulated surface. In case the magnetic field is orthogonal to the boundary, a constant value of the magnetic potential leads to impose a Dirichlet BC:

$$\varphi_{\boldsymbol{M}} =\bar{\varphi} \qquad \text{on} \qquad \partial\Omega_{\text{pot}} \tag{6}$$

where $\bar{\varphi}$ is the prescribed magnetic potential value at the boundary $\partial\Omega_{\text{pot}}$. The magnetic force is then computed by integrating over the surface of the permanent magnet the Maxwell's stress tensor T.

$$\mathbf{F}_{\boldsymbol{MAG}} = \int_{\partial\Omega_{MAG}} \mathbf{n}\, T\, dS = -\frac{1}{2}\int_{\partial\Omega_{MAG}} [\mathbf{n}(\mathbf{H}\cdot\mathbf{B}) + (\mathbf{n}\cdot\mathbf{H})\mathbf{B}^T]\, dS \qquad \text{on} \qquad \partial\Omega_{\text{MAG}} \tag{7}$$

The problem is then solved via the Finite Element Method (FEM) through COMSOL Multiphysics® with serendipity quadratic FEs.

Piezoelectric vibration energy harvester

The typical PVEH is a layered cantilever beam as represented in Fig. 1b. In this work we assume linear behavior of the material [8,9]. The modelling of the beam is carried out by considering only the so called 31-mode and through a lumped-parameter approach [10] with one degree-of-freedom (dof) both for the displacement field and the voltage. The electromechanical equations of motion are derived by using the Euler-Lagrange equations obtaining the following differential system that has been implemented in a MATLAB© code:

$$\begin{cases} m\ddot{W}(t) + c_m\dot{W}(t) + k_L W(t) - \theta V(t) = f_{ext} \\ C\,V(t) + \theta\dot{W}(t) + V(t)/R = 0 \end{cases} \tag{9}$$

where W is the tip displacement of the cantilever, V the voltage output from the piezo. m is the inertial term, c_m the linear damping coefficient, k_L the linear stiffness, C the capacitance of the piezo and θ the piezoelectric coupling coefficient. f_{ext} is the forcing function, and it includes the magnetic force.

Simulation

Magnetic force

To numerically investigate the shielding technique, we simulate the magnetic force between two magnetic systems as depicted Fig. 1c, in repulsive configuration with both or only one shielded magnets. The main magnet is a cube with a side length of 3 mm and a magnetization **M** equal to 1.32 T. The cover is realized with the same material and magnetization. In the case in which both magnets are shielded, we consider two values as cover thickness (0.5 mm, 1.0 mm) and four values of gap distance h (0.5, 1.0, 1.5, 2.0 mm). In the case in which only one of the cubic PMs is shielded, we consider the cover thickness of 1 mm and two values of gap distance (1.0 and 1.5 mm). We compare all the cases with the layout without shielding. According to the reference system of Fig. 1b we are interested in the z-component of the magnetic force with respect to the relative distance on the same axis. All the plots in the Figs. 2 and 3 show that, using the shielding on one or both PMs, it is possible to tighten the force-distance curves. The cover induces an inversion in sign in such way that the gradient of the force is modified, and the sharpening is the result.

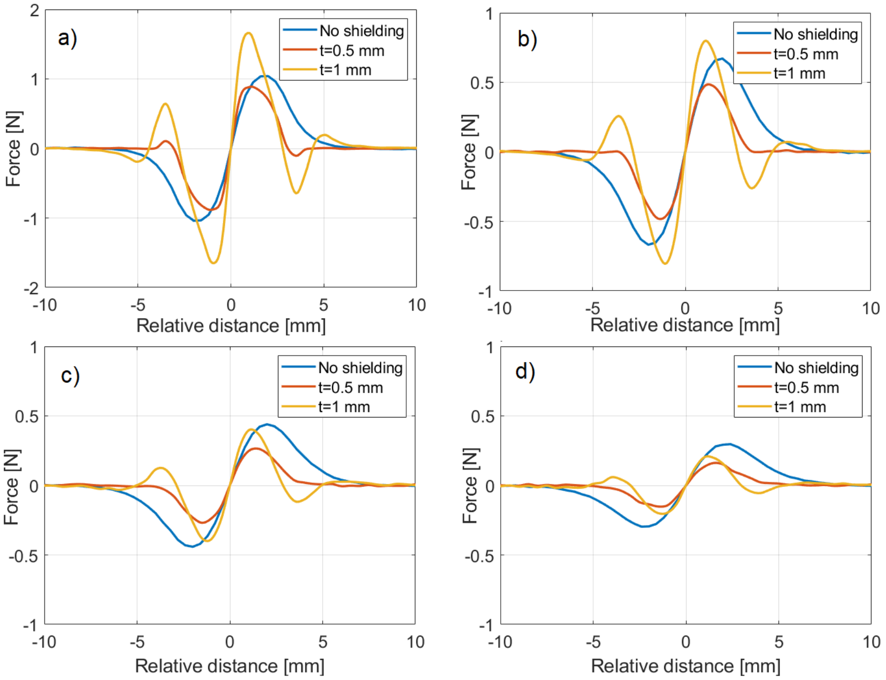

Figure 2. z-component of the magnetic force with both shielded PMs and without shielding for different gaps: a) 0.5 mm, b) 1.0 mm, c) 1.5 mm d) 2.0 mm

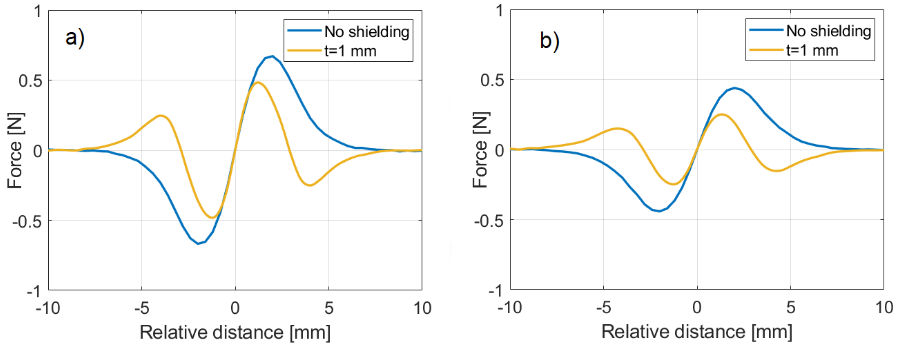

Figure 3. z-component of the magnetic force with only one shielded PM and without shielding for different gaps: a) 1.0 mm, b) 1.5 mm

Magnetically plucked piezoelectric energy harvester

In this section we use the computed magnetic force to analyze the plucking mechanism on a PVEH. The data of the cantilever are summarized in the Table 1.

Material	ρ [kg/m^3]	E [GPa]	n [-]	d_{31} [pC/N]	ε_{33}^s[-]	t[µm]	Width [mm]	Length [mm]
Titanium	4500	115	0.3	-	-	65	1.5	15
PZT	7500	60	0.3	212	2000	280 per layer (series)	1.5	15

Table 1. Physical parameters and geometry of the bimorph

We simulate the response of the cantilever by solving the differential system of Eq. (9) by using the presented magnetic forces in repulsive configuration as f_{ext}. We look at the peak of power output for varying velocity of the interaction in the range 0.1-10 m/s (i.e. velocity of the moving magnet in Fig. 1c supposed at constant velocity) with a value of the resistor $R = 100$ kΩ. The instantaneous power is computed trough the Joule's Law:

$$P = V^2/R \tag{10}$$

To compare two oscillators working at the same frequency of 366.06 Hz, we use in the layout without shielding two magnets with dimensions 5 x 5 x 3 mm^3 and in the case with the shielding a cubic main magnet with a length side of 3 mm and a cover thickness of 1 mm to get the same global dimensions. The results in Fig. 3b show that the adoption of shielding induces a huge increment of peak power in the low-speed range (0.1-2.6 m/s), that is typical for the human movements. On the contrary, the case without shielding is connected with the absolute maximum power, reached for quite large velocity (4.5 m/s).

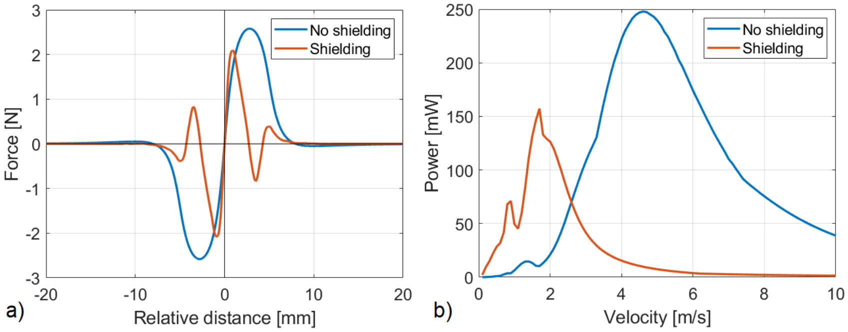

Figure 4. a) z-component of the magnetic force with and without shielding b) peak power for different velocities of the seismic system with a resistor $R = 100k\Omega$

Experimental validation

We present in this section an experimental validation of the concept in case only one of the couple of interacting PMs is shielded for gap values of 1.0 mm and 1.5 mm. The details of the setup are summarized in [11]. The supposed principle is confirmed because by considering only the experimental curves in the plots of Fig.5, the shielded layout (S) shows a sharper behavior with respect the unshielded case (NS) in terms of force-distance curve. On the other side, the comparison between numerical results and experiments with shielding (S) shows some discrepancies in the inversion of sign which may be the subject of further studies and works. Anyway, the physics of the phenomenon is well captured as well as the peak force.

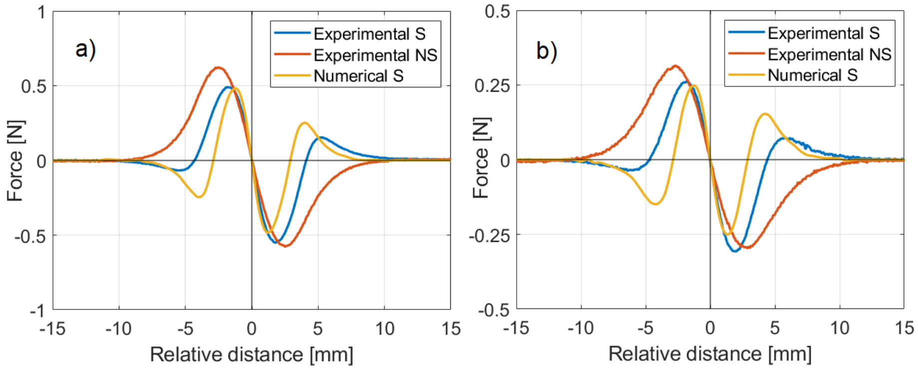

Figure 5. z-component of the magnetic force for the case of a) gap 1.0 mm and b) 1.5 mm. NS: no shielding, S: with shielding

Conclusions

In this work we studied a strategy to sharpen the force-displacement magnetic curve between PMs through a specific arrangement of the magnetization of additional polarized ferromagnetic material to a main magnet. The aim is to realize a dynamical load as impulsive as possible for PVEH systems. We proposed a concept, a theoretical formulation, and a computational study together with an experimental validation that confirms the principle. The numerical investigation applied to a PVEH case study shows that the technique can be used to set the performance of the harvester depending on the velocity of the magnetic interaction. The shielded harvester obtains a larger amount of power (until 150 mW) than the unshielded one in a very low speed range (0.1-2.6 m/s). The technique can be also applied in a more general context of the mechanics (e.g. actuation and sensing) and this opens new motivations to improve the modelling and to implement this technique also at the MEMS scale.

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